A mathematical programming model for integrating production and procurement transport decisions

Manuel Díaz-Madroñero, Josefa Mula*, David Peidro

Universitat Politècnica de València, Research Centre on Production Management and Engineering (CIGIP), Plaza Ferrándiz y Carbonell, 2, 03801 Alcoy (Alicante) Spain

ARTICLE INFO

Keywords:
Production planning
MRP
Transport planning
Mathematical programming

ABSTRACT

In this paper, we propose a new mathematical programming model for integrating production and procurement transport planning decisions in manufacturing systems in a unique optimization model. This problem was introduced conceptually and dubbed as MRP IV by Díaz-Madroñero et al. (2012) to extend the current MRP (material requirement planning) systems. This proposal simultaneously considers material, production resources capacities and procurement transport planning decisions with different shipping modes (such as full-truckload, less-than-truckload and milk-run) in the supply chain to avoid suboptimal results, which are usually generated due to sequential and independent plans. We considered an industrial automobile company to validate the proposed model using real world data. The results obtained by the MRP IV proposed model, in terms of total planning costs and transport efficiency indicators, are better than those obtained in the current heuristic procedures followed in the company under study.

1. Introduction

Nowadays, supply chains are characterized by their members' considerable offshoring, and most are located in countries with lower labor costs and less strict regulations. In this context, production planning and materials procurement in current industrial firms are highly influenced by transportation planning, and cannot hence be considered independent processes. However, most current production planning systems calculate production, procurement and transport planning decisions separately by generating plans that have to be rescheduled or manually amended given their suboptimality from an economic perspective or their infeasibility due to capacity constraints [1].

The material requirement planning (MRP) system, proposed by Orlicky [2], continues to be the most widely used production planning system. MRP is based on the explosion of a BOM, which translates the production plan into the required amounts and time instants by considering inventory levels and lead times for raw materials and components [3,4]. The MRP system does not consider any capacity constraint, and this led to evolution toward closed-loop MRP and MRP II (manufacturing resource planning) systems [5] and extended the original MRP system with master schedule calculations and capacity requirements planning or CRP. In the 1990s, the MRP II system evolved to MRP III (money resource planning) [6] and ERP (enterprise resource planning) systems [7], whose main goal was to incorporate all business functions (finances, sales, production, etc.) into a single decision-making system. Yet despite the features added in recent decades, such as supply chain management or transport issues and new communications and IT features, the main element of ERP systems still

E-mail addresses: fcodiama@cigip.upv.es (M. Díaz-Madroñero), fmula@cigip.upv.es (J. Mula), dapeipa@cigip.upv.es (D. Peidro).

lies in the logic of the original MRP systems. In current competitive business environments, firms need to optimize their production planning decisions, hence the demand of MRP models with optimization features. According to Yenisey [8], although the earliest MRP approaches did not provide optimal solutions, the maximization of profit and constraints related to demand or productive resources was gradually included in order to optimize the production and procurement plans that derived from MRP systems. The works by Karni [9] and Billington et al. [10] can be considered original contributions in this area as they propose mathematical programming models for MRP problems under capacity constraints. Other authors like [8,11–16] have addressed MRP optimization by different approaches based on mathematical programming solution methods in deterministic scenarios.

Regarding transport planning, Coyle et al. [17] defined transport as the physical link that connects fixed points in a logistics supply chain. Hence transport processes are fundamental parts in supply chains because they enable raw materials and finished goods to flow among suppliers, manufacturers, warehouses and retailers. Hence transport planning can contribute to increase the degree of supply chain managers' satisfaction by supporting the planning and control of material flows [18] and the delivery of superior value to end consumers [19]. According to Fleischmann et al. [20], two types of transport processes can occur in a supply chain. On the one hand, the supply of materials from external suppliers to a production site [21–26], and, on the other hand, the distribution of products from a factory to customers [27–30]. According to Chandra and Fisher [31], the integration of production and transportation planning decisions is a way to reduce costs and to increase efficiency in operations in industrial firms [32,33]. In line with this, several surveys have been published on simultaneous production and transport planning [34–39]. Most of these reviewed models simplify transport processes by considering only direct shipments or the full truck load shipping mode, and by disregarding the less-than-load or routes distribution mode. The simultaneous consideration of production and transport routes is addressed by a research area, called the production and routing problem, which has developed in the last few years [40,41]. The production routing problem consists of a manufacturing plant, from which products are sent to customers by determining the necessary distribution transport routes and the corresponding inventory levels for both the production plant and customers in order to minimize the corresponding total costs [31,42–47].

Transport planning in these distribution problems is usually the supplier's responsibility, but there are some main exceptions, e.g., in the automobile industry, where the manufacturer controls transport from its suppliers. In this case, transport planning also occurs on the procurement side [20]. In such contexts, integration related to production and transport procurement decisions is usual lacking, so production planning is done separately and sequentially in relation to the transport planning of raw materials and components from suppliers to manufacturing centers [38]. Therefore, optimization models and tools for simultaneous production and procurement transport planning processes that contemplate different forms of transport, e.g., full truck load, less-than-load and milk-run, etc., are needed [48].

In this context, in [1] we conceptually approached the problem of integrating into a unique optimization model the MRP II production system, which is widely used by companies around the world, and procurement transport planning decisions, of increasing relevance because global supplier network developments are expanding. Therefore, we dubbed our conceptual approach as MRP IV as an extension of previous MRP systems, which is the basis of our proposal. Other extensions of MRP systems have also arisen with different denominations, such as DDMRP [49], Green-MRP [50] and MRP/sfx [51], which respectively address aspects of driven demand, sustainability and shop floor orientation.

Here, the present paper proposes a mathematical programming formulation for modeling and solving the MRP IV problem, which integrally addresses material, production, capacity and transport requirement planning to support a manufacturing company's decision making. The main contributions of this paper are summarized as follows: introducing a novel mathematical programming model for integrating production and procurement transport decisions in a unique optimization model by considering several shipping modes, e.g., full truck load (FTL), less-than-load (LTL) and milk-run, and model validation in a real-world company that belongs to the automobile industrial sector. In this context, other alternative approaches that address the integration of production and procurement transport planning problems have been proposed by Kuhn and Liske [52,53], who combine the economic lot sizing and vehicle routing problems, and called it the economic lot and supply scheduling problem (ELSSP); and Hein and Almeder [54] who extend it from a capacitated lot sizing and vehicle routing problem (CLSVRP) perspective.

The rest of the paper is organized as follows: Section 2 presents describes the MRP IV problem. Section 3 presents the mathematical programming model proposed to address the MRP IV problem. Section 4 offers an application of the proposed model in the automobile industry by presenting an evaluation of the obtained results and highlighting the managerial implications of the proposal. Finally, Section 5 provides the conclusions drawn and future research lines.

2. MRP IV description

Díaz-Madroñero et al. [1] and Mula et al. [55] originally introduced the conceptual model for the MRP IV problem, which is the starting point used to develop the mathematical programming model explained in this paper. Other academic studies have suggested analytical models for solving the production-transportation problem [56–61]. For an extensive review on production-transportation analytical models, we refer readers to [37,38] and [41]. It is important to highlight that most of the conducted studies address production and distribution planning to customers rather than production and procurement transport planning, as addressed herein. Regarding this restricted research area, the proposals by Kuhn and Liske [52,53], Hein and Almeder [54], Chen and Sarker [62] and Liotta [63] are highlighted. In line with this, Kuhn and Liske [52] com-

Table 1.
Main characteristics of reviewed articles.

		Kuhn and Liske [52]	Kuhn and Liske [53]	Chen and Saker [62]	Hein and Almeder [54]	MRP IV
Demand		Static	Static	Static	Dynamic	Dynamic
Periods		One and infinite	One and infinite	One and infinite	Multiple	Multiple
Finished goods		Multiple	Multiple	Multiple	Multiple	Multiple
Raw materials		Multiple	Multiple	Multiple	Multiple	Multiple
Production system issues	Stages	Single stage	Single stage	Single stage	Single stage	Single stage
	Capacity	•	•	•	•	•
	Overtime and undertime					•
	Backlogs					•
Inventory issues	Finished goods warehouse	•	•	•	•	•
	Components and raw materials warehouse	•	•	•	•	•
	Capacity					•
	Safety stock					•
Transport issues	Modes	One	One	One	One	Several
	Fleet of vehicles	Homogeneous	Homogeneous	Homogeneous	Homogeneous	Homogeneous
	Travel time between nodes					•
	Distance dependent cost	•	•	•	•	•
	Fixed cost per vehicle		•		•	•
	Fixed cost per stop					•
Costs	Setup	•	•	•	•	
	Inventory holding	•	•	•	•	•
	Transport	•	•	•	•	•
	Manufacturing					•
	Purchasing		•			•
Main Assumptions	Suppliers			Each supplier offers only one kind of part to the manufacturer		
	Suppliers location				Geographically dispersed in close proximity to the production plant	
	Production	Finished goods have a common production cycle Production plant only can manufacture one item at a time	Finished goods may be produced by different production cycles, although a common basic period still exists			
	Routes	Each route contains only input materials for a single end item	Each route contains only input materials for a single end item	Same delivery cycle time for all suppliers	Every vehicle route starts and ends during the same period	
Application	Artificially generated instances	•	•	•	•	
	Industrial data					•

bine an ELSP and a VRP to represent the production system and the collection of raw materials from a set of suppliers, respectively, in the so-called economic lot and supply scheduling problem (ELSSP), and use a common production cycle time for each finished good manufactured under constant demand. Later Kuhn and Liske [53] relax this assumption by considering that each finished good can be produced with different production cycles, and emphasize the economic advantages of the power-of-two policy compared with a common cycle approach. In this context, Chen and Sarker [62] develop a solution method based on metaheuristic algorithms to integrate milk-run transport procurement with the production stage. Based on previous studies by Kuhn and Liske [52,53], Hein and Almeder [54] propose a MIP formulation for the capacitated lot sizing and supply side vehicle routing problem (CLSVRP). It comprises an inventory routing problem (IRP) and a CLSP with dynamic and discrete demand in conventional and JIT scenarios, and with and without raw materials inventories, respectively. Table 1 presents the characteristics of the previous contributions in terms of demand, planning horizon, number of finished goods and raw materials, productions, inventory and transport issues, considered costs, as well as the main assumptions and applications as regards the present proposal. As shown in Table 1, two main groups of proposals can be found. On the one hand, those models which assume a static stationary demand with an infinite period, and on the other hand, those which consider dynamic demand over multiple time periods. Depending on this aspect, the formulation and properties of the proposed models differ. However, some distinct aspects are shared between both groups of proposals, such as modeling multiple finished goods and raw materials, and considering a single and capacitated production stage that is supplied from raw materials and a components warehouse and which manufactures finished goods that can also be stored in their corresponding warehouse. Regarding transport issues, all these previous articles consider a homogeneous fleet of vehicles and distance-dependent costs. In this sense, setup and inventory holding costs are also included in the objective function of these previous contributions. The main assumptions were divided into four groups: suppliers, location of suppliers, production system and routes. Regarding supplier assumptions, Chen and Saker [62] are the only authors who consider that each supplier can only offer one type of component or raw material to the manufacturer. As regards production systems, Kuhn and Liske [52] assume that finished goods have a common production cycle, and that production plants can only manufacture one finished good at a time. Later Kuhn and Liske [53] consider different production cycles, but with a common basic period. According to Chen and Saker [62], transport routes have the same delivery cycle time for all suppliers, while Kuhn and Liske [52,53] impose that each route contains only the input materials needed to manufacture a single finished good. Regarding dynamic demand approaches, we can highlight the assumption made by Hein and Almeder [54], who consider that all suppliers are located in close proximity to production plants and, hence, each vehicle route has to start and end during the same time period.

In comparison to our proposal, this is one of the main differences found because the MRP IV model considers transit times between suppliers that can be located far away from manufacturing plants, with travel distances of more than a time period. Our model also contemplates several road transport modes (FTL, LTL and milk run) and costs per stop in each supplier or manufacturing plant, as well as transport distance based costs and fixed costs per vehicle. The objective function also includes the manufacturing and purchasing costs of components and raw materials. Regarding the production system and inventory, the MRP IV model considers the possibility of manufacturing finished goods in extra time and backlogging demand with high penalization costs, as well as capacitated warehouses for component and raw materials and safety stocks, respectively. Finally, only the MRP IV is validated with a case study and a real world manufacturing firm that belongs to the automotive industry.

Thus the MRP IV problem can be stated as follows:

Given:

- Customers demand for each finished good during each planning period.
- Bill of materials (BOM) for each finished good. A general structure is assumed; i.e., an input material could form part of several different products. Here one supplier could supply different parts that belong to several finished goods.
- Initial demand backorders and initial inventory levels for each finished good, raw material and component.
- Safety stock for each finished good, raw material and component.
- Supply lead time for each raw material and component.
- Scheduled receptions for each raw material and component.
- Production system costs: variable production costs, purchasing costs of raw materials and components, inventory holding costs, backordered demand costs, undertime costs and overtime costs of productive resources.
- Production capacity of available productive resources.
- Manufacturing time required to produce each finished good.
- Setup times (if required).
- Production lot size (if required).
- Inventory capacity in the manufacturing plant warehouse.
- Dimensions of raw materials and components.
- Purchasing lot size for each raw material and component.
- Distances and transit times between nodes (suppliers and production plant).
- Transport costs: traveled distance costs, waiting and loading and unloading costs. Other complementary costs can be considered, such as urgent deliveries, overload, discounts, etc.
- Transport capacity of available vehicles.
- Shipping modes: different shipment modes can be considered depending on the ordered amount of raw materials and components, and on suppliers' geographic location; e.g., FTL, LTL or routes, and milk-run.
- Shipment frequency from suppliers that use the milk-run shipping mode.
- Special shipping units required for transporting raw materials and components, e.g., racks, pallets, etc.

To determine:

- The Master production schedule (MPS).
- Overtime and undertime hours of the available productive resource.
- Purchasing plan for raw materials and components.
- Number of vehicles, loads and routes.

- Inventory levels for each finished good, raw material and component at the end of each period.
- Demand backorder levels for each finished good at the end of each period.

The main goal to meet is:

- Minimizing total costs, including production, inventory and transport costs.

Subject to:

- Production capacity constraints.
- Safety stock and inventory capacity constraints.
- Transport capacity constraints.

Moreover, the following assumptions are made:

- Only a productive resource that restricts the manufacturing of finished goods is considered.
- The shipping mode is considered pre-assigned for each supplier; e.g., FTL shipments correspond to those suppliers with the highest volume of orders. Shipments by routes or LTL are indicated for those suppliers with small volumes of orders and which are located at middle to long distances from the manufacturer so that shipments can be consolidated by designing routes. Finally, milk-run routes correspond to those suppliers located very close to each other and to the manufacturer with higher order volumes that are received several times a day via routes that are repeated with a given frequency.
- The supply lead time is considered null for finished products and raw materials, and for components supplied by the milk-run shipping mode, because the manufacturing and transit times from very close suppliers are cut compared to the transport times for FTL and LTL suppliers.

3. MRP IV formulation

This section proposes a mixed integer mathematical programming formulation for the MRP IV problem. The nomenclature defines the sets of indices, parameters and decision variables for the proposed model (Table 2).

Model formulation is as follows:

$$
\begin{aligned}
Minimize\, z = & \sum_{i\in J}\sum_{t} cp_{it}\cdot P_{it} + \sum_{i\in C}\sum_{k}\sum_{t} cpc_{it}\cdot QRF_{ikt} + \sum_{i\in C}\sum_{l}\sum_{t} cpc_{it}\cdot QRD_{ilt} \\
& + \sum_{i\in C}\sum_{t} cpc_{it}\cdot QRM_{it} + \sum_{i\in J}\sum_{t} ci_{it}\cdot INVTF_{it} + \sum_{i\in C}\sum_{t} ci_{it}\cdot INVTC_{it} \\
& + \sum_{i\in J}\sum_{t} cbo_{it}\cdot B_{it} + \sum_{t} \mathrm{cov}_t\cdot OVT_t \\
& + \sum_{i}\sum_{k}\sum_{t} ckm\cdot DistF_i\cdot Y_{ikt} + \sum_{l}\sum_{t}\sum_{s}\sum_{i} ckm\cdot DistR_{si}\cdot X_{ltsi} \\
& + \sum_{i}\sum_{k}\sum_{t} cst\cdot Y_{ikt} + \sum_{l}\sum_{t}\sum_{s}\sum_{i=0} cst\cdot LX_{ltsi} \\
& + \sum_{g}\sum_{s\in TM\cup np}\sum_{i\in TM\cup np}\sum_{t} ckm\cdot f_g\cdot DistR_{si}\cdot M_{gsit} \qquad (1)
\end{aligned}
$$

The objective function (1) corresponds to the minimization of the total production and transport planning costs. It includes production costs, acquisition costs of raw materials and components, the inventory cost of finished goods, raw materials and components, overtime costs of productive resources, backordered demand costs, transport costs associated with FTL, routes or LTL (including expected costs per stop) and milk-run shipments. Here cost components have been considered as time-dependent. Nevertheless, for specific problems with time-independent cost components, index t could be removed from the cost coefficients of the objective function.

Subject to:

$$
\begin{aligned}
& INVTF_{i,t-1} + P_{i,t-lt_i} + SR_{it} - B_{i,t-1} + B_{it} - INVTF_{it} = d_{it} \\
& \forall i \in J, \forall t \qquad (2)
\end{aligned}
$$

$$
\begin{aligned}
& INVTC_{i,t-1} + \sum_{k} QRF_{ik,t-lt_i} + \sum_{l} QRD_{il,t-lt_i} + QRM_{it} \\
& + SR_{it} - INVTC_{it} = \sum_{j} \alpha_{ji}\cdot P_{jt} \qquad \forall i \in C, \forall t \qquad (3)
\end{aligned}
$$

Table 2.
Nomenclature.

Set of indices	
I,S	Set of finished goods, components and raw materials, suppliers, manufacturing plant and virtual node
TF	Set of suppliers with the FTL shipment mode
TR	Set of suppliers with routes or the LTL shipment mode
TM	Set of suppliers with the milk-run shipment mode
G	Set of graphs of the milk-run routes
T	Set of time periods
J	Set of finished goods
C	Set of components and raw materials
K	Set of available trucks for the FTL shipping mode
L	Set of available trucks over the planning horizon for routes or the LTL shipping mode
Parameters	
d_{it}	Demand of finished good i during time period t
lt_i	Lead time of supplier i
$INVTF_{i0}$	Initial inventory level of finished good i in the manufacturing plant
$INVTC_{i0}$	Initial inventory level of component i in the manufacturing plant
SR_{it}	Scheduled receptions of component i during time period t
B_{i0}	Initial backorders of finished good i
α_{ji}	Quantity of i to produce a unit of finished good j
CAP_t	Available capacity of the productive resource during time period t
AR_i	Time required to produce a unit of product i in the productive resource
SS_i	Safety stock of component i
$WCAP$	Available inventory capacity for the components in the manufacturing plant
sz_i	Size of a unit of product i
$DistF_i$	Distance to the manufacturing plant from supplier i
$DistR_{si}$	Distance from supplier s to supplier i
TT_{si}	Transit time from node s to node i
$TRCAP$	Maximum transport capacity per truck
np	Node that corresponds to the manufacturing plant
nv	Virtual node that corresponds to the beginning of each route
f_g	Pick up frequency in each node per period in graph g
cp_{it}	Variable cost of the normal production of a unit of finished good i during time period t
cpc_{it}	Purchasing cost of component i during time period t
ci_{it}	Inventory holding cost of product i during time period t
cbo_{it}	Backorder cost of product i during time period t
cov_t	Cost of 1 overtime hour of the productive resource during time period t
ckm	Cost per kilometer
cst	Stop cost for picking products at suppliers
Decision variables	
P_{it}	Quantity of product i to be produced during time period t
QRF_{ikt}	Quantity of product to order to supplier i by the FTL shipping mode on truck k during time period t
QRD_{ilt}	Quantity of product to order to supplier i by routes or the LTL shipping mode on truck l during time period t
QRM_{it}	Quantity of product to order to supplier i by the milk-run shipping mode during time period t
$INVTF_{it}$	Inventory of finished good i at the end of time period t
$INVTC_{it}$	Inventory of component i at the end of time period t
B_{it}	Backorder of finished good i at the end of time period t
UNT_t	Undertime hours of the productive resource during time period t
OVT_t	Overtime hours of the productive resource during time period t
SRF_{ikt}	Space occupied by the amount of QRF to be shipped by the FTL shipping mode on truck k during time period t
SRD_{ilt}	Space occupied by the amount of QRD to be shipped by routes or the LTL shipping mode on truck l during time period t
SRM_{git}	Space occupied by the amount picked in supplier i in graph g by the milk-run shipping mode during time period t
Y_{ikt}	1 if truck k travels from the supplier to the production plant in the FTL shipping mode, 0 otherwise
X_{ltsi}	1 if truck l departs from node s to node i during time period t, 0 otherwise
LX_{ltsi}	1 if truck l arrives to node i from node s during time period t, 0 otherwise
YR_{lst}	1 if truck l visits node s during time period t, 0 otherwise
YRD_{lit}	1 if SRD is higher than zero, 0 otherwise
M_{gsit}	1 if the truck in graph g departs from node i to node s during time period t, 0 otherwise
YM_{git}	1 if the truck in graph g arrives at i during time period t, 0 otherwise
WR_{lst}	Auxiliary variable used for subtours elimination constraints
WM_{gst}	Auxiliary variable used for subtours elimination constraints in each graph g

$$\sum_{i \in J} P_{it} AR_{ir} + UNT_t - OVT_t = CAP_t \qquad \forall t \tag{4}$$

$$SRF_{ikt} = sz_i \cdot QRF_{ikt} \qquad \forall i \in C \cap \{TF \cup TR\}, \forall k, \forall t \tag{5}$$

$$SRF_{ikt} \leq TRCAP \cdot Y_{ikt} \qquad \forall i \in C \cap \{TF \cup TR\}, \forall k, \forall t \tag{6}$$

$$SRD_{ilt} = sz_i \cdot QRD_{ilt} \qquad \forall i \in C \cap TR, \forall l, \forall t \tag{7}$$

$$SRM_{git} = sz_i \cdot \frac{QRM_{it}}{f_g} \qquad \forall i \in C \cap TM, \forall g, \forall t \tag{8}$$

$$\sum_{l} \sum_{i \in TR \cup nv} X_{lt,np,i} = 0 \qquad \forall t \tag{9}$$

$$\sum_{l} \sum_{s \in TR \cup np} X_{lts,nv} = 0 \qquad \forall t \tag{10}$$

$$\sum_{t} \sum_{i \in TR \cup np} X_{lt,nv,i} \le 1 \qquad \forall l \tag{11}$$

$$\sum_{t} \sum_{s \in TR \cup nv} X_{lts,np} \le 1 \qquad \forall l \tag{12}$$

$$\sum_{l} \sum_{t} \sum_{i \in TR \cup np} X_{lt,nv,i} \le L \tag{13}$$

$$\sum_{l} \sum_{t} \sum_{s \in TR \cup nv} X_{lts,np} \le L \tag{14}$$

$$\sum_{s \in TR \cup nv} LX_{ltsi} = YRD_{l,it} \qquad \forall i \in TR, \forall l, \forall t \tag{15}$$

$$SRD_{ilt} \le TRCAP \cdot YRD_{lit} \qquad \forall i \in C \cap TR, \forall l, \forall t \tag{16}$$

$$\sum_{i \in TR \cap C} \sum_{t} SRD_{ilt} \le TRCAP \qquad \forall l \tag{17}$$

$$\sum_{i \in TR \cup np} X_{ltsi} = YR_{lst} \qquad \forall s \in TR, \forall l, \forall t \tag{18}$$

$$X_{ltsi} = LX_{l,t+TT_{si},si} \qquad \forall i \in TR \cup np, \forall s \in TR \cup nv, \forall l, \forall t \tag{19}$$

$$\sum_{i \in TR \cup np} X_{ltsi} = \sum_{i \in TR \cup nv} LX_{ltis} \qquad \forall s \in TR \cup np, \forall l, \forall t \tag{20}$$

$$\sum_{i \in TM \cup np} M_{gsit} = \sum_{i \in TM \cup np} M_{gist} \qquad \forall s \in TM, \forall g, \forall t \tag{21}$$

$$\sum_{s \in TM} M_{g,np,s,t} = 1 \qquad \forall g, \forall t \tag{22}$$

$$\sum_{s \in TM} M_{g,s,np,t} = 1 \qquad \forall g, \forall t \tag{23}$$

$$\sum_{s \in TM \cup np} M_{gsit} = YM_{git} \qquad \forall i \in TM, \forall g, \forall t \tag{24}$$

$$\sum_{i \in TM \cup np} M_{gsit} = YM_{gst} \qquad \forall s \in TM, \forall g, \forall t \tag{25}$$

$$\sum_{g} YM_{git} = 1 \qquad \forall i \in TM, \forall t \tag{26}$$

$$\sum_{i \in TR} \left(SRM_{git} \cdot YM_{git} \right) \le TRCAP \qquad \forall g, \forall t \tag{27}$$

$$WR_{lst} - WR_{li,t+TT_{si}} + (TR - 1) \cdot LX_{l,t+TT_{si},si} \le TR - 2 \qquad \forall i, s \in TR, \forall l, \forall t \tag{28}$$

$$WM_{gst} - WM_{git} + (TM - 1) \cdot M_{gtsi} \leq TM - 2 \quad \forall i, s \in TM, \forall g, \forall t \tag{29}$$

$$\sum_{i \in C} INVTC_{it} \leq WCAP \quad \forall t \tag{30}$$

$$INVTC_{it} \geq SS_i \quad \forall i \in C, \forall t \tag{31}$$

$$B_{i,t=T} = 0 \quad \forall i \in J \tag{32}$$

$$UNT_t, OVT_t, SRF_{ikt}, SRD_{ilt}, WR_{lst}, WM_{gst} \geq \mathbf{0} \quad \forall i, \forall s, \forall r, \forall k, \forall l, \forall g, \forall t \tag{33}$$

$$P_{it}, INVTF_{it}, INVTC_{it}, B_{it}, QRF_{ikt}, QRD_{ilt,} QRM_{it} \geq \mathbf{0} \in Z \quad \forall i, \forall k, \forall l, \forall t \tag{34}$$

$$X_{ltsi}, LX_{ltsi}, YRD_{lit}, YR_{lst}, Y_{ikt,} M_{gsit,} YM_{git} \in \{0, 1\} \quad \forall i, \forall s, \forall k, \forall l, \forall g, \forall t \tag{35}$$

Constraints (2) and (3) establish inventory balance equations for finished goods and raw materials and components, respectively. For finished goods, the inputs in Constraint (2) correspond to produced amounts, scheduled receptions and the inventory at the end of the previous period, while outputs are the demand levels for each product. For raw materials and components, the inputs in Constraint (3) refer to the amounts to procure from each supplier, received for each transport shipping mode, and the scheduled receptions and inventory levels for previous period. Outputs correspond to the consumptions for each raw material and component obtained by exploiting the BOM. Production amounts are limited by the availability of a group of shared resources. Both constraints consider the lot-for-lot optimization technique for each time period. If the consideration of other economic trade-offs or physical factors requires the addition of other lot-sizing optimization techniques, they should be incorporated through new constraint formulations.

Constraint (4) considers the capacity limits for these productive resources. Similarly to Mula et al. [64], decision variable OVT_t is not limited by any upper bound, but is penalized with its corresponding cost in the objective function while UNT_t is incorporated in order to avoid infeasibilities. Constraint (5) determines load size (in linear meters) for the ordered amounts to each supplier with FTL shipping mode. Constraint (6) corresponds to transport capacity limitations for full trucks; thus load size does not exceed the truck's total capacity in linear meters. The proposed model allows the components and raw materials to be delivered by full trucks from the suppliers previously associated with the routes shipping mode if this is more advantageous according to the corresponding incurred costs. Constraint (7) is the equivalent to Constraint (5), but refers to routes or the LTL shipping mode. Constraint (8) determines shipment sizes for the milk-run mode by dividing the total size of the ordered amounts by the corresponding pick up frequency. The open nature of transport routes is given by the following equations. Constraint (9) ensures that no truck can depart from the manufacturing plant to another node, while Constraint (10) determines that no truck can arrive at the virtual node used as a departure node on each route. Moreover, Constraint (11) determines that each truck can only depart at most once from the virtual node towards any shipping routes mode supplier all along the planning horizon. Constraint (12) ensures that each truck that arrives from any supplier can only arrive to the production plant, as a maximum, once throughout the planning horizon. Constraint (13) states that only the number of total available vehicles (L) can depart from a virtual node as a maximum. Similarly, Constraint (14) determines the limitation of the trucks that arrive at the production plant from any shipping route mode supplier throughout the planning horizon. Constraints (15) and (16) establish the condition of visiting every LTL shipping supplier in such a way that truck l visits the corresponding supplier, but only if the size (in meters) of the quantity to order on each truck l exceeds zero. Constraint (17) corresponds to transport capacity limitations in such a way that the total loaded amounts by a truck at each visited supplier is less than the truck's total capacity. Constraint (18) determines that each truck l can depart only once from each supplier. Constraint (19) is included to provide a better understanding of the model in relation to the movement of trucks throughout the time expanded network. Specifically, Constraint (19) shows the equivalence of decision variables X_{ltsi} and LX_{ltsi} by considering the lag time associated with the transit time between nodes s and i. Given this equivalence, the balance equation of the traffic flow in each node is determined by Constraint (20). Unlike the open character of the conventional routes shipping mode, milk-run routes begin and end at the manufacturing plant, as in classical vehicle routing problem (VRP) models. Thus Constraints (21) to (27) correspond to the typical constraints related to this problem [65]. Constraint (21) determines the vehicles balance flow equation in each node by establishing that the number of trucks that leaves a node must equal the number of trucks that arrived at that node. Constraints (22) and (23) determine that the vehicle associated with graph g starts and ends its route in the node that corresponds to the production plant. Constraints (24), (25) and (26) state that each supplier can be visited only by one truck in a single graph. Constraint (27) establishes transport capacity limitations in such a way that the total amounts collected at each supplier on each route are less than the truck's capacity to transport them. This equation presents a product of a binary decision variable and a continuous decision variable that results in a mixed integer nonlinear programming model. In order to avoid this nonlinearity, this expression can be easily linearized using a new auxiliary variable, as indicated by Williams [66]. Constraints (28) and (29) correspond to the equations of Miller et al. [67] for the subtours elimination on conventional routes and milk-run routes, respectively. In the latter, constraint formulation is immediate, while in the time expanded network routes case, the original equation had to be adapted to the rest of the model. Constraints (30) and (31) establish the limits that relate to the inventory levels of raw materials and components. In Constraint (30) the total inventory on hand is limited by the total warehouse capacity, while Constraint (31) states that the inventory level for each component and raw material should be above the safety stock. Constraint (32) ensures that demand backorders are zero at the end of the planning horizon. Constraint (33) establishes nonnegativity conditions for decision variables, and Constraint (34) imposes integrality conditions. Finally, Constraint (35) indicates the binary character of the rest of the decision variables.

Another possibility is to include fixed costs for vehicle use, as well as stoppage and traveled distance costs. According to Desaulniers [68], the fixed costs associated with each vehicle must be high enough to avoid suboptimal solutions.

In the proposed integrated production and procurement transport planning approach, production planning decisions (production amounts per time period and inventory) interrelate with transport planning decisions (shipments per period, routes, traveled distances and number of vehicles) through inventory and capacity constraints (3) and (4), provided that a single warehouse and productive resource are considered. In the sequential approach transport planning decisions are decomposed into three independent transport planning models that relate to each shipping mode. The entire transport and production planning problem can be decomposed into three integrated transport and production planning, but independent, problems according to the three shipping modes by assuming at least one raw material warehouse and one productive resource for each shipping mode.

4. Application to an automobile supply chain

The supply chain to which the proposed model MRP IV is applied belongs to the automobile sector. This supply chain consists of a set of 32 second-tier suppliers. They send raw materials and components to a first-tier supplier which manufactures automobile seats to send them to a car assembler. Specifically, the application of the proposed model focuses on three different models manufactured in the seat supplier plant located in Assenede (Belgium) from where the car assembler plant located in Gent (Belgium) is supplied according to a just-in-time production system. In this sense, it is important to highlight the seat manufacturer assemblies and deliveries of seats in a synchronized way to the car assembler's assembly lines. However, second-tier suppliers, which supply raw materials and parts to the seat assembler, do not produce and deliver in this synchronized way according to a just-in-time system, rather the seat assembler's material requirement planning system is adopted as the basis of their production and transportation plans. Depending on their geographical location to the seat manufacturing plant, and the volume of the components and raw materials needed, the mid-term planning at the seats manufacturer assigns the most convenient transport mode for procurement from each supplier. For the seats manufacturing plant, the available suppliers send their products by the FTL shipping mode, or by conventional routes or the LTL shipping mode, since there is no group of suppliers in the vicinity of the production plant to establish milk-run routes.

Currently, production and procurement transport planning are solved separately. First, the production and procurement plan is calculated by an ERP system based on standard MRP II. Nevertheless, the company only uses the MRP module for material supply planning because it is considered that no capacity problems will arise as the car seat assembly supplier is a flexible plant, plus there is the possibility of using extra capacity from other plants in the industrial group [64]. On a regular weekly basis, the company receives the DCI (daily call in) or production program with a 10-day planning horizon from the automobile assembler, which acts, along with the BOM of each seat, as input data for the production planning module. Second, procurement transport planning is solved by taking into account the output of the production planning module, and by using an heuristic procedure based on the spreadsheet described by Peidro et al. [69] and Mula et al. [22], for the FTL shipping mode, while a manual heuristic procedure is used for routes or the LTL shipping mode. For all the existing suppliers, a group of more than 10 employees uses these procedures to manually plan transport processes.

The assumptions made to carry out the computational experiment are summarized as:

- Customer demand is stated for three finished products that are representative of all the products manufactured by the seats manufacturer.
- Decision variables P_{it}, $INVTF_{it}$ and B_{it} are considered integer.
- If the production system cannot produce the quantities demanded by the automobile assembler, backordered demand for end products is allowed, but at a high cost penalty.
- The assembly line is the only productive resource that restricts the manufacturing of finished goods.
- The MRP IV model is run every Monday when demand values are updated with a 10-day horizon that corresponds to the reception of the DCI. These values are considered firm orders.

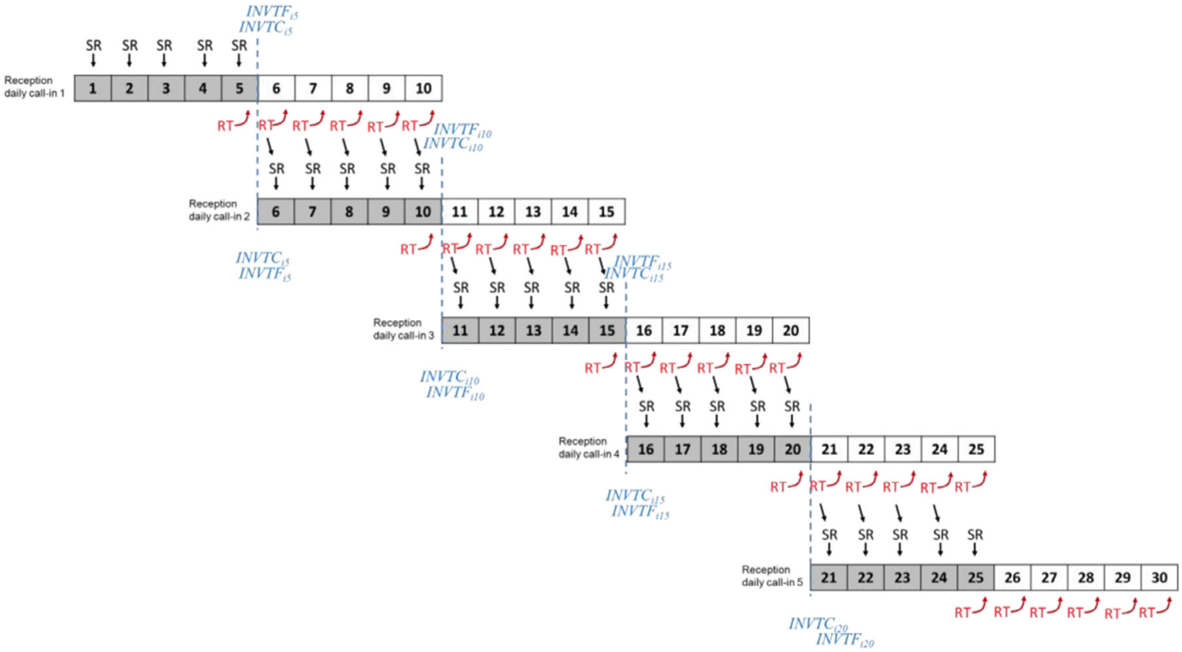

Fig. 1. Rolling horizon heuristic mechanism (I).

- Given the computational effort needed to calculate solutions, a maximum run time is set at 15 min.
- The shipping mode for each supplier is known in advance and is set according to the mid-term planning by the manufacturing seat firm.
- Fixed costs are considered for truck use.

Detailed input data can be found at: http://personales.upv.es/fcodiama/AMM/AMM_DiazMadroñero_Data.pdf

According to Kuhn and Liske [52], to reproduce the sequential planning approach conducted in the company without any integration, the MRPDet model [64] is executed. The corresponding BOM explosion acts as an input of a transportation planning model for the FTL shipping model based on the spreadsheet described in Díaz-Madroñero et al. [70] and Peidro et al. [69], and a model for transportation planning for routes or the LTL shipping model.

4.1. Computational experiments

Computational experiments were carried out by using the rolling planning horizon concept [71]. If a 6-week planning horizon is considered (30 daily periods), which corresponded to a planning segment from the automobile assembler, the obtained problem could be too complex to be solved by a commercial MIP solver. So in order to solve the problem for all the considered periods, a rolling horizon heuristic procedure was chosen. Such heuristics have been applied in production planning problems [72,73] and transport planning problems [74,75]. Rolling horizon heuristics are based on dividing the planning horizon into smaller subhorizons to solve repeated mathematical programming models associated with the obtained planning subhorizons.

The rolling horizon mechanism is shown in Figs. 1 and 2. In each iteration of the heuristic, the subhorizon was divided into two parts:

(i) A frozen part, in which the planned amounts calculated in the previous iteration were received by transportation to begin producing the amounts imposed by the previous iteration with no stockouts of components and raw materials.
(ii) A part in which the amounts to produce (*P*), the amounts of components and raw materials, and the corresponding transportation planning (*RT*) were calculated by considering the inventory level available at the end of the last period in the first planning subhorizon half in the previous iteration (*INVTF* and *INVTC*).

These calculated quantities were frozen and then production amounts and scheduled receptions (*SR*) were considered in the first subhorizon half in the next iteration, respectively. This process was repeated until the entire planning horizon was covered. In each iteration, the corresponding mixed integer linear programming model was solved coinciding with the reception of each DCI.

The proposed MRP IV model, and those used to compare the sequential planning approach conducted in the seats manufacturing firm with no kind of integration, adopted the considered previously assumptions. All these models were implemented by using the MPL modeling language [76]. Their resolutions were carried out by the Gurobi solver [77] in a computer with two Intel Xeon 2.93 GHz processors and 48 GB RAM memory.

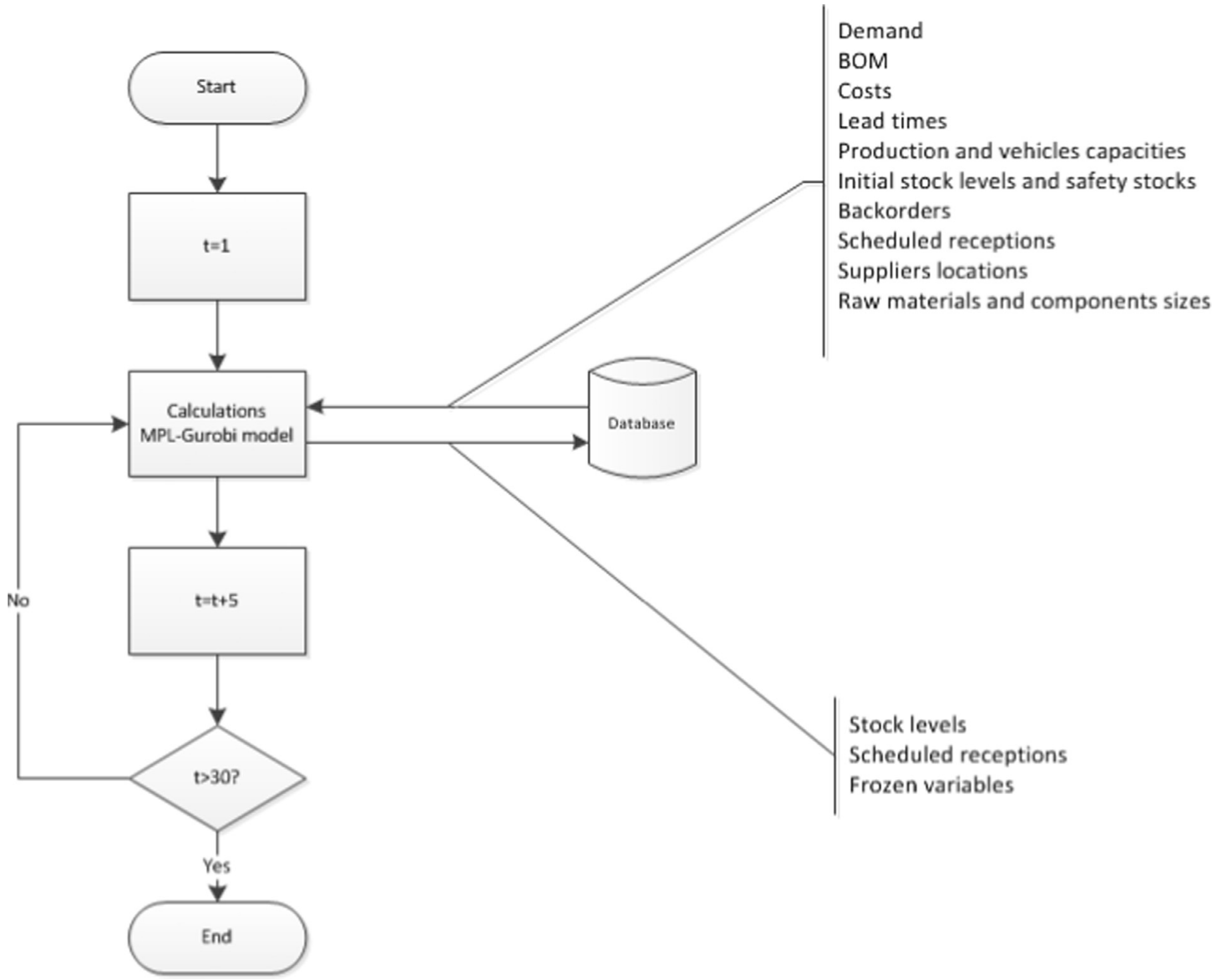

Fig. 2. Rolling horizon heuristic mechanism (II).

4.2. Evaluation of the results

In this study, the results obtained by carrying out the computational experiments according to the previous rolling horizon procedure for the proposed MRP IV model, and those used to simulate the sequential planning approach conducted in the seats manufacturing firm with no kind of integration, were compared. The evaluation of the results focused on the following aspects: (1) computational efficiency; (2) planning costs; and (3) transport planning indicators.

4.2.1. Computational efficiency

Table 3 summarizes the computational effort needed to solve each model for both the integrated and sequential approaches, and for each execution. Column iterations indicate the number of iterations needed to obtain an optimal solution. The number of decision variables, integer variables, constraints and nonzero elements from the constraints matrix related to the model, along with the density matrix, are also shown. Parsing and solution times (CPU time) are also included. Finally, the solution gap is indicated.

The results on the computational effort of the models were obtained by setting an upper limit of CPU time at 900 s and a stopping criterion for the gap of 1% in such a that the solution process stopped if either of these two criteria was met. As the evaluated models had the same structure and input data of the same size for each execution, the values associated with each model size (variable, integer and constraints) were equal for each one. However, the values directly related to the solution process and the required computational effort, such as the number of iterations, parsing time and CPU time, could have different values, except when the model reached the limit of 900 s during the solution process.

The bottom of the table shows the results for the sequential approach without integration. The total values obtained by this approach were significantly higher than the integrated MRP IV approach as for the total number of variables and integer variables because the variables in each model were duplicated. Conversely, the number of constraints and nonzero

Table 3.
Computational efficiency.

		Model	*Iterations*	*Variables*	*Integer*	*Constraints*	*Nonzero elements*	*Matrix density (%)*	*Parsing time (s)*	*CPU time (s)*	*Gap*
Integrated approach	Exec.1	MRPIV_1	1,55,756	228,670	69,490	1,534,843	5,451,788	0.0016%	117.00	276.00	0.8809%
	Exec.2	MRPIV_2	670,035	228,670	69,490	1,534,858	5,449,853	0.0016%	116.00	901.00	1.0176%
	Exec.3	MRPIV_3	722,145	228,670	69,490	1,534,858	5,449,853	0.0016%	122.00	901.00	1.1328%
	Exec.4	MRPIV_4	420,210	228,670	69,490	1,534,858	5,449,853	0.0016%	120.00	901.00	1.1552%
	Exec.5	MRPIV_5	374,876	228,670	69,490	1,534,858	5,449,853	0.0016%	116.00	901.00	1.1011%
Sequential approach	Exec. 1	MRPDet1	728	2000	90	2109	4551	0.1800%	0.28	0.06	0.6532%
		FTL1	1424	126,010	37,030	74,360	263,310	0.0030%	1.65	5.96	0.4357%
		Routes1	1,501,273	200,975	72,730	290,290	1,903,640	0.0030%	80.00	901.00	5.3892%
		TOTAL1	1,503,425	328,985	109,850	366,759	2,171,501		81.93	907.02	
	Exec. 2	MRPDet2	32	2000	90	2109	4656	0.1100%	1.97	0.19	0.0000%
		FTL2	1511	126,010	37,000	74,360	263,310	0.0030%	1.33	5.15	0.3094%
		Routes 2	1,096,596	200,975	72,730	290,290	1,903,640	0.0030%	89.00	900.00	5.9578%
		TOTAL2	1,098,139	328,985	109,820	366,759	2,171,606		92.30	905.34	
	Exec. 3	MRPDet3	22	2000	90	2109	4656	0.1100%	0.66	0.05	0.0000%
		FTL3	1395	126,010	37,000	74,360	263,310	0.0030%	0.83	5.91	0.3501%
		Routes 3	1,195,270	200,975	72,730	290,290	1,903,640	0.0030%	83.00	900.00	7.9671%
		TOTAL3	1,196,687	328,985	109,820	36,6759	2,171,606		84.49	905.96	
	Exec. 4	MRPDet4	28	2000	90	2109	4656	0.1100%	0.61	0.01	0.0553%
		FTL4	1230	126,010	37,000	74,360	263,310	0.0030%	1.62	7.11	0.3826%
		Routes 4	1,779,764	200,975	72,730	290,290	1,903,640	0.0030%	85.00	901.00	5.0991%
		TOTAL4	1,781,022	328,985	109,820	366,759	2,171,606		87.23	908.12	
	Exec. 5	MRPDet5	30	2000	90	2109	4656	0.1100%	0.66	0.05	0.1889%
		FTL5	1372	126,010	37,000	74,360	263,310	0.0030%	1.32	6.31	0.6541%
		Routes 5	1,135,056	200,975	72,730	290,290	1,903,640	0.0030%	82.00	900.00	6.4462%
		TOTAL5	1,136,458	328,985	109,820	366,759	2,171,606		83.98	906.36	

Table 4.
Comparison of the total costs in the integrated and sequential approaches.

	Integrated approach MRP IV	Sequential approach	Savings	Savings (%)
Total costs	€35,402,268	€36,436,788	€1,034,520	15.45[a]
Total overtime costs	€95,966	€155,623	€59,657	38.33
Total inventory costs	€1,957,386	€1,908,635	€−48,751	−2.55
Total transport costs	€3,586,108	€4,609,722	€1,023,614	22.14

[a] Excluding fixed costs (production and raw materials purchasing).

elements was considerably higher in the integrated approach because of the simultaneous consideration of the inventory, production and transportation restrictions. This fact was confirmed by the longer parsing time required as a prelude to the resolution. In general, CPU times were similar for both approaches as models MRPDet and FTL were easily solved (0.19 s and 7.11 s, respectively), while the route models needed nearly 900 s to obtain a solution in all cases given their highly combinatorial nature. This explained the large number of iterations required for the resolution, as seen in the corresponding column, and they were an order of magnitude above the number of iterations required for solving the integrated models. The deviation of the obtained solution to the lower bound of the problem was also superior in the route models as a maximum gap of 7.9671% was obtained during the third execution. This could, therefore, determine the overall optimality of the sequential approach compared to the maximum gap of 1.1552% of the integrated MRP IV model obtained during the fourth execution. The largest number of restrictions in the integrated model made the universe of solutions smaller and, therefore, the resolution process proved more effective for finding a solution that came closer to the optimal one in the same CPU time. The total CPU time required for the five rolling horizon executions to solve the production and transportation planning problem was 3880 s (65 min) for the integrated approach, while the sequential approach needed 4532 s (76 min). However, we noted that despite these calculation times seeming excessive, such tactical problems are not run every day and are, therefore, acceptable solution times [78].

4.2.2. Planning costs

Table 4 presents the costs associated with the production and transport planning carried out according to the sequential and integrated MRP IV approach, calculated for 30 periods according to the proposed rolling horizon mechanism. Furthermore, in order to compare the savings obtained by the integrated approach compared to the sequential approach, formula (36) proposed by Kuhn and Liske [52] was considered. Table 4 offers the savings that correspond to all the different considered costs in both absolute numbers and percentages.

$$Savings = \frac{\mathrm{Cost}_{sequential} - \mathrm{Cost}_{integrated}}{\mathrm{Cost}_{sequential}} \cdot 100\% \quad (36)$$

Table 5.
Comparison of the transport planning indicators of the integrated and sequential approaches.

	Integrated approach MRP IV	Sequential approach	Improvement **(%)**
Total traveled kilometers	960,154	1,254,754	23.48
Kilometers traveled by vehicle	925.00	969.67	4.6
Number of vehicles for the full truck shipping mode	1020	1236	17.48
Number of vehicles for the routes shipping mode	18	58	68.97
Average occupation level of vehicles for the full truck load shipping mode	94.54%	75.14%	25.82
Average occupation level of vehicles for the routes shipping mode	99.89%	92.20%	8.34
Transport cost per finished good unit	€97.57	€125.31	22.14

Regarding costs, production, inventory and overtime costs were considered to compute the total costs for the first halves for each planning subhorizon during each execution (except in implementation 5, where such costs were considered for all the periods), but also the purchase costs of raw materials and components and transport costs for the entire period of each model execution.

Regarding the most significant savings in absolute terms, transport costs were firstly identified, followed by overtime costs, while inventory costs became slightly worse because the sequential approach exactly matched the inventory levels and the established safety stocks since the quantities to order calculated by the MRPDet model were not modified during the transportation planning process. Consequently, the use of transport resources became worse, so more trucks would be needed to transport the ordered quantities. According to the typical behavior of an MRP model, raw materials and components orders are made during the last possible period needed to manufacture finished goods, which could involve resorting to overtime if demand was higher than the manufacturing production capacity during such period. In this case, overtime costs were higher in the sequential model than in the integrated model which advanced the manufacturing of finished goods to periods with lower demand levels and, therefore, the available manufacturing capacity was better adjusted. Production and raw materials purchasing costs remained unchanged; this was because they are indispensable for meeting the demand for both the sequential and integrated approaches and could, therefore, be considered fixed costs for this purpose in the contemplated planning horizon.

According to the main factors that might influence the savings that can be achieved by the integrated method, it is important to highlight demand levels, production capacity, lot sizes, transport network capacity and safety stocks. It is foreseen that higher demand levels with no increased production capacity will lead to more overtime costs in both models, but with a slight increase in the sequential model, which delays the demand immediately prior to it becoming necessary, and without considering transportation factors. Furthermore, the established supply and manufacturing lot sizes and/or higher safety stocks would result in higher inventory, production and transport costs. In short, the integrated approach better optimizes transport capacity and overtime usage, and even the achieved savings would improve with worse conditions of demand variability, fixed lot sizes and higher safety stocks.

After considering the fixed nature of the production and raw materials' purchasing costs, the following suggestion was made: the relative savings obtained by the integrated approach should be calculated after deducting these costs from the total costs in the same way that costs have been considered in Chandra and Fisher [31], Bard and Nananukul [44,45], Boudia and Prins [78] and Kuhn and Liske [52], among others. Hence the relative saving for the sequential approach obtained by the integrated model, which was calculated by excluding fixed costs, was 15.45%, and 2.84%, respectively, without being excluded. Nevertheless, absolute savings were more than one million euros, which could be considered a significant saving, especially in successive periods of over 1 year. Furthermore, the integrated approach at least ensured the results obtained by the sequential approach and therefore, never increased the results compared to the sequential procedure, as shown by Kuhn and Liske [52].

4.2.3. Indicators related to transport planning

Table 5 shows the values for the transportation planning indicators obtained by the MRP IV integrated approach and the sequential approach with no integration. These indicators were used in the manufacturing seats company to assess its transportation planning.

The indicators offered by the integrated approach shown in Table 5 significantly improved those obtained by the sequential approach. First, the total number of kilometers traveled lowered by nearly three hundred thousand kilometers, the equivalent to 23.48%. This was due mainly to the reduction in the number of trucks used in the integrated approach compared to the sequential approach, so the sum of the distances traveled by all these trucks decreased. However, although the average of kilometers traveled by truck was also more favorable in the integrated approach, it did not generate such a substantial improvement as the indicator of total distance traveled. In this case, the improvement was 44.67 kms by truck, the equivalent to 4.61%, caused by the fewer trucks used by the integrated approach compared to the sequential approach. Specifically, the integrated approach used 216 full trucks and 40 vehicles for the routes shipping model, less than the sequential approach with no integration for the 30 periods considered in the planning horizon.

The proportion of vehicles for the FTL shipping mode compared to routes was slightly higher in the integrated approach than in the sequential one because the possibility of simultaneous production, inventory and transportation planning allowed to take the advantage offered by the FTL shipping mode compared to the routes shipping mode. Occupation of FTL significantly improved in the integrated approach, which resulted in an average occupation that came close to 95% of the transport capacity offered by trucks, compared to the 75.14% results obtained by the sequential approach. The advantages of integrated planning were also reflected in the occupation values obtained for the routes shipping mode, which reached 99.89% of the available capacity compared to the result of 92.20% with the sequential approach. In short, the integrated approach obtained better results compared to the sequential approach with no integration in total distance, average distance traveled per vehicle, number of trucks used and occupation. This was reflected in the improved overall transportation costs, as indicated in the previous section. In turn, this implied a reduction in the transport unit cost to incur in each manufactured finished good unit. This indicator was obtained by dividing the total transport costs obtained by the total number of units manufactured in the planning horizon. In this case, the reduction was €27.74, which meant an improvement of 22.14%.

According to the data provided by the company, the maximum number of considered nodes was 14. However, routes did not tend to be formed by more than four stops because, in the integrated mode, transport resources started being used more efficiently (trucks were filled more), and occasionally completely loaded trucks were used instead of organizing deliveries on less filled trucks via routes. We can conclude that the challenging problems according to difficulty are the milk-run problem, and LTL and FTL given the problem's combinatorial characteristic.

Finally, the resulting production and transportations plans are shown for both the integrated and sequential planning approaches for finished goods 1 and raw materials in terms of the production and procurement amounts while executing the rolling horizon the second time to provide differences between both plans. See the link below: http://personales.upv.es/fcodiama/AMM/AMM_DiazMadroñero_Data2.pdf

4.3. Managerial implications

After comparing the results obtained by the integrated and sequential approaches in a case study based on a real-world company that belongs to the automobile industry, we conclude that the integrated MRP IV approach is able to increase the degree of satisfaction in the planning and decision-making processes without causing any explosive growth of computational efforts. Indeed from the following main input data, the integrated approach could provide production managers with: demand, inventory levels, bill of materials and manufacturing data, supplier locations, logistics constraints and associated unit costs; and output data related to: MPS, purchasing plan, the vehicles required for each transport mode, optimal routes and costs. Thus overtime and procurement transport costs considerably improve compared with a traditional sequential approach. Moreover, the management of procurement transport resources is enhanced through increased vehicle utilization and by cutting traveled distances and the number of required trucks. Since fewer trucks are needed, the integrated MRP IV approach could make the management of vehicles in unloading docks, and of incoming raw materials and components, easier as the traveled distance is shorter. This would reduce emissions of CO_2 and other gases associated with using combustion engines, which would imply consequent and evident environmental benefits.

Another improvement is its ability to automate calculations without having to use different information systems or moving information from the ERP to spreadsheets, with the risk of data loss. The proposed MRP IV model also helps avoid suboptimal results due to manual replannings done based on personal judgments, and on the experience of the planners in the company to which it is applied. The staff that is currently in charge of these planning tasks could evaluate and analyze the solutions obtained or transferred to other departments and reassigned to other functions within the company. Apart from obtaining more favorable planning, the new integrated model offers the possibility of consolidating all the production, inventory and transportation information in the same database. Even so, this MRP IV model could be used as the nucleus of any ERP or APS (advanced production system). In fact as far we know, APS commercial software, say APO or i2, addresses both problems (production planning and transport planning) in a sequential optimization/heuristics way by coordinating independent modules or blocks [79–81], rather than in an integrated way by simultaneously optimizing production planning and transport planning (routing and loading), as proposed in this paper.

5. Conclusions

This work has developed a mixed integer mathematical programming model, called MRP IV, to address production and procurement transport planning in an integrated fashion to avoid suboptimal results. The proposed model extends traditional MRP II by including the typical transportation modes used in industrial environments to send raw materials and components from suppliers to manufacturing plants, such as FTL, LTL or routes and milk-run.

The proposed model has been validated using data from a real-world firm that belongs to the automobile industry in order to simultaneously compare the production and procurement transport planning obtained by the MRP IV model with the sequential planning done with the manual procedures used in the company under study. In order to avoid time-consuming calculations in the model resolution, a rolling horizon heuristic procedure has been considered. The proposed model presents better results in terms of total planning costs (production, inventory and transport costs) and transport efficiency (traveled kilometers, number of vehicles and vehicles occupation) without causing a computational effort explosion. Here the company studies the application and implementation of integrated production and procurement transport planning approaches, and their link with current information systems, but in accordance with the company's corporative strategy during a multinational purchasing process.

In this case, experiments based on an application study were carried out according to the planning horizon, the input data provided by the company and the planning method usually addressed in the automobile sector, where part of the planning horizon is frozen. This is useful for adapting production and transportation plans to demand uncertainty, while computation complexity diminishes. Nevertheless, further research is required to provide new experiments with several artificial generated data sets and different time horizon sizes and number of products to test their influence on computational efficiency. The other limitations in this work are related to: (i) the transport shipping mode for each supplier is determined prior to executing the model according to the mid-term planning used in the company; (ii) the proposed solution method is not efficient enough in CPU time terms for problems that involve a larger number of suppliers and more products and components because many integer and binary variables exist. Therefore, the development of soft computing techniques, evolutionary algorithms and metaheuristics to help obtain solutions in acceptable times could be necessary. These sophisticated solution methods could help enrich MRP IV through further research, especially transport aspects by considering distance constrained or time constrained routing problems, and in accordance with current legislation on driver rest periods, including time windows for visits to suppliers, and time windows for unloading at the manufacturing plant; or by contemplating the possibility of dividing the amounts to be collected at each supplier to transport them in different vehicles on different paths; moreover, each vendor can be visited by more than one vehicle during each period, as in the split delivery VRP [82]. Future studies could also introduce social responsibility issues by adding environmental (e.g. gases emissions by vehicles and manufacturing plants) and social (e.g. employees' working conditions) criteria and the inherent uncertainty related to unknown or uncontrolled parameters, such as transport lead times, by proper modeling approaches, such as fuzzy mathematical programming or robust optimization. Finally in the future, more extensions could be foreseen to readapt MRP systems to further company needs. For instance, to the new Industry 4.0 context where production processes should be capable of smartly coordinating themselves and cooperating; e.g., being self-managing, with other value chain actors by minimizing their costs [83–85].

Acknowledgment

This research has been carried out within the framework of the project funded by the Spanish Ministry of Economy and Competitiveness entitled 'Operations design and Management of Global Supply Chains' (GLOBOP) (Ref. DPI2012-38061-C02-01).

References

[1] M. Díaz-Madroñero, J. Mula, D. Peidro, A conceptual model for MRP IV, in: J. Hernández, P. Zarate, F. Dargam, B. Delibašić, S. Liu, R. Ribeiro (Eds.), Decision Support Systems – Collaborative Models and Approaches in Real Environments, 121, Springer, Berlin, Heidelberg, 2012, pp. 14–25.
[2] J. Orlicky, Material Requirements Planning, McGraw-Hill, New York, 1975.
[3] W.J. Hopp, M.L. Spearman, Factory Physics, Waveland Press, 2011.
[4] T.E. Vollmann, W.L. Berry, D.C. Whybark, F.R. Jacobs, Manufacturing Planning and Control for Supply Chain Management, McGraw-Hill, Irwin, New York, 2005.
[5] O. Wight, Manufacturing Resource Planning: MRP II: Unlocking America's Productivity Potential, John Wiley & Sons, 1984.
[6] Schollaert F. Money resource planning, MRP-III: the ultimate marriage between business logistics and financial management information systems. Library Albert; 1994.
[7] L. Wylie, ERP: a vision of the next-generation MRP II, Comput. Integr. Manuf. 300 (1990) 1–5.
[8] M.M. Yenisey, A flow-network approach for equilibrium of material requirements planning, Int. J. Prod. Econ. 102 (2006) 317–332, doi:10.1016/j.ijpe.2005.04.002.
[9] R. Karni, Integer linear programming formulation of the material requirements planning problem, J. Optim. Theory Appl. 35 (1981) 217–230, doi:10.1007/BF00934577.
[10] P.J. Billington, J.O. McClain, L.J. Thomas, Mathematical programming approaches to capacity-constrained MRP systems: review, formulation and problem reduction, Manag. Sci. 29 (1983) 1126–1141.
[11] L. Escudero, P. Kamesam, Production planning via scenario modelling, Ann. Oper. Res. 10 (1993) 24–45, doi:10.1007/BF02025089.
[12] K. Rota, C. Thierry, G. Bel, Capacity-constrained MRP System: A Mathematical Programming Model Integrating Firm Orders, Forecasts and Suppliers, Université de Toulouse II Le Mirail Département d'Automatique, 1997.
[13] A.R. Clark, Optimization approximations for capacity constrained material requirements planning, Int. J. Prod. Econ. 84 (2003) 115–131, doi:10.1016/S0925-5273(02)00400-0.
[14] D. Giglio, R. Minciardi, Modelling and optimization of multi-site production systems in supply chain networks, in: Proceedings of the 2003 IEEE International Conference on Systems Man Cybernetics, SMC '03 5–8 Oct. 2003, 3, 2003, pp. 2678–2683.
[15] S. Noori, M.R. Feylizadeh, M. Bagherpour, F. Zorriassatine, R.M. Parkin, Optimization of material requirement planning by fuzzy multi-objective linear programming, Proc. Inst. Mech. Eng. Part B J. Eng. Manuf. 222 (2008) 887–900, doi:10.1243/09544054JEM1014.
[16] R.J. Milne, C.-T. Wang, C.-K.A. Yen, K. Fordyce, Optimized material requirements planning for semiconductor manufacturing, J. Oper. Res. Soc. 63 (2012) 1566–1577, doi:10.1057/jors.2012.1.
[17] J.J. Coyle, E.J. Bardi, C.J. Langley, J.J. Coyle, The Management of Business Logistics: A Supply Chain Perspective, 7th ed., Mason, Ohio, 2002.
[18] L.M. Ellram, Supply-chain management: the industrial organisation perspective, Int. J. Phys. Distrib. Logist. Manag. 21 (1991) 13–22, doi:10.1108/09600039110137082.
[19] M. Christopher, D. Towill, An integrated model for the design of agile supply chains, Int. J. Phys. Distrib. Logist. Manag. 31 (2001) 235–246, doi:10.1108/09600030110394914.
[20] B. Fleischmann, H. Kopfer, C. Sürie, Transport planning for procurement and distribution, Supply Chain Management and Advanced Planning, Springer, 2015, pp. 225–240.
[21] A. Sarkar, P.K.J. Mohapatra, Maximum utilization of vehicle capacity: a case of MRO items, Comput. Ind. Eng. 54 (2008) 185–201, doi:10.1016/j.cie.2007.07.003.
[22] J. Mula, F. Campuzano-Bolarin, M. Díaz-Madroñero, K.M. Carpio, A system dynamics model for the supply chain procurement transport problem: comparing spreadsheets, fuzzy programming and simulation approaches, Int. J. Prod. Res. 51 (2013) 4087–4104, doi:10.1080/00207543.2013.774487.
[23] T. Schöneberg, A. Koberstein, L. Suhl, A stochastic programming approach to determine robust delivery profiles in area forwarding inbound logistics networks, OR Spectr. 35 (2013) 807–834, doi:10.1007/s00291-013-0349-0.

[24] M. Díaz-Madroñero, D. Peidro, J. Mula, A fuzzy optimization approach for procurement transport operational planning in an automobile supply chain, Appl. Math. Model. 38 (2014) 5705–5725, doi:10.1016/j.apm.2014.04.053.
[25] M. Shafiei Kisomi, M. Solimanpur, A. Doniavi, An integrated supply chain configuration model and procurement management under uncertainty: a set-based robust optimization methodology, Appl. Math. Model. 40 (2016) 7928–7947, doi:10.1016/j.apm.2016.03.047.
[26] S. Pazhani, J.A. Ventura, A. Mendoza, A serial inventory system with supplier selection and order quantity allocation considering transportation costs, Appl. Math. Model. 40 (2016) 612–634, doi:10.1016/j.apm.2015.06.008.
[27] C. Archetti, K.F. Doerner, F. Tricoire, A heuristic algorithm for the free newspaper delivery problem, Eur. J. Oper. Res. 230 (2013) 245–257, doi:10.1016/j.ejor.2013.04.039.
[28] M. Furkan Uzar, B. Çatay, Distribution planning of bulk lubricants at BP Turkey, Omega 40 (2012) 870–881, doi:10.1016/j.omega.2012.01.008.
[29] M. Nikolić, D. Teodorović, Vehicle rerouting in the case of unexpectedly high demand in distribution systems, Transp. Res. Part C Emerg. Technol. 55 (2015) 535–545, doi:10.1016/j.trc.2015.03.002.
[30] E.E. Zachariadis, C.D. Tarantilis, C.T. Kiranoudis, Integrated distribution and loading planning via a compact metaheuristic algorithm, Eur. J. Oper. Res. 228 (2013) 56–71, doi:10.1016/j.ejor.2013.01.040.
[31] P. Chandra, M.L. Fisher, Coordination of production and distribution planning, Eur. J. Oper. Res. 72 (1994) 503–517, doi:10.1016/0377-2217(94)90419-7.
[32] A. Degbotse, B.T. Denton, K. Fordyce, R.J. Milne, R. Orzell, C.T. Wang, IBM blends heuristics and optimization to plan its semiconductor supply chain, Interfaces 43 (2013) 130–141, doi:10.1287/inte.1120.0642.
[33] K. Katircioglu, R. Gooby, M. Helander, Y. Drissi, P. Chowdhary, M. Johnson, et al., Supply chain scenario modeler: a holistic executive decision support solution, Interfaces 44 (2014) 85–104, doi:10.1287/inte.2013.0725.
[34] B. Bilgen, I. Ozkarahan, Strategic tactical and operational production-distribution models: a review, Int. J. Technol. Manag. 28 (2004) 151, doi:10.1504/IJTM.2004.005059.
[35] J.J. Bravo, C.J. Vidal, Freight transportation function in supply chain optimization models: a critical review of recent trends, Expert Syst. Appl. 40 (2013) 6742–6757, doi:10.1016/j.eswa.2013.06.015.
[36] Ş.S.S. Erengüç, Simpson N.C.C., A.J. Vakharia, Integrated production/distribution planning in supply chains: an invited review, Eur. J. Oper. Res. 115 (1999) 219–236, doi:10.1016/S0377-2217(98)90299-5.
[37] B. Fahimnia, R.Z. Farahani, R. Marian, L. Luong, A review and critique on integrated production–distribution planning models and techniques, J. Manuf. Syst. 32 (2013) 1–19.
[38] J. Mula, D. Peidro, M. Díaz-Madroñero, E. Vicens, Mathematical programming models for supply chain production and transport planning, Eur. J. Oper. Res. 204 (2010) 377–390.
[39] C.J. Vidal, M. Goetschalckx, Strategic production-distribution models: a critical review with emphasis on global supply chain models, Eur. J. Oper. Res. 98 (1997) 1–18.
[40] Y. Adulyasak, J.-F. Cordeau, R. Jans, The production routing problem: a review of formulations and solution algorithms, Comput. Oper. Res. 55 (2015) 141–152, doi:10.1016/j.cor.2014.01.011.
[41] M. Díaz-Madroñero, D. Peidro, J. Mula, A review of tactical optimization models for integrated production and transport routing planning decisions, Comput. Ind. Eng. 88 (2015) 518–535, doi:10.1016/j.cie.2015.06.010.
[42] Y. Adulyasak, J.-F. Cordeau, R. Jans, Formulations and branch-and-cut algorithms for multivehicle production and inventory routing problems, INFORMS J. Comput. 26 (1) (2013) 103–120.
[43] Y. Adulyasak, J.-F. Cordeau, R. Jans, Optimization-based adaptive large neighborhood search for the production routing problem, Transp. Sci. 48 (2014) 20–45, doi:10.1287/trsc.1120.0443.
[44] J.F. Bard, N. Nananukul, The integrated production-inventory-distribution-routing problem, J. Sched. 12 (2009) 257–280.
[45] J.F. Bard, N. Nananukul, A branch-and-price algorithm for an integrated production and inventory routing problem, Comput. Oper. Res. 37 (2010) 2202–2217.
[46] M. Boudia, M.A.O. Louly, C. Prins, A reactive GRASP and path relinking for a combined production-distribution problem, Comput. Oper. Res. 34 (2007) 3402–3419.
[47] M. Boudia, M.A.O. Louly, C. Prins, Fast heuristics for a combined production planning and vehicle routing problem, Prod. Plan. Control 19 (2008) 85–96.
[48] M. Díaz-Madroñero, J. Mula, D. Peidro, A review of discrete-time optimization models for tactical production planning, Int. J. Prod. Res. 52 (2014) 5171–5205, doi:10.1080/00207543.2014.899721.
[49] C.A. Ptak, C. Smith, Demand driven Material Requirements Planning (DDMRP), Industrial Press, Incorporated, 2016.
[50] S.A. Melnyk, R.P. Sroufe, F.L. Montabon, T.J. Hinds, Green MRP: identifying the material and environmental impacts of production schedules, Int. J. Prod. Res. 39 (2001) 1559–1573, doi:10.1080/00207540010022980.
[51] P.B. Nagendra, MRP/sfx: a kanban-oriented shop floor extension to MRP, Prod. Plan. Control 10 (1999) 207–218.
[52] H. Kuhn, T. Liske, Simultaneous supply and production planning, Int. J. Prod. Res. 49 (2011) 3795–3813.
[53] H. Kuhn, T. Liske, An exact algorithm for solving the economic lot and supply scheduling problem using a power-of-two policy, Comput. Oper. Res. 51 (2014) 30–40, doi:10.1016/j.cor.2014.04.012.
[54] F. Hein, C. Almeder, Quantitative insights into the integrated supply vehicle routing and production planning problem, Int. J. Prod. Econ. 177 (2016) 66–76, doi:10.1016/j.ijpe.2016.04.014.
[55] J. Mula, M. Díaz-Madroñero, D. Peidro, A conceptual model for integrating transport planning: MRP IV, in: J. Frick, B.T. Laugen (Eds.), Advances in Production Management Systems. Value Networks: Innovation, Technologies, and Management editors, Springer, Berlin, Heidelberg, 2012, pp. 54–65.
[56] M. Darvish, H. Larrain, L.C. Coelho, A dynamic multi-plant lot-sizing and distribution problem, Int. J. Prod. Res. 54 (2016) 6707–6717, doi:10.1080/00207543.2016.1154623.
[57] S. Khalifehzadeh, M. Seifbarghy, B. Naderi, Solving a fuzzy multi objective model of a production–distribution system using meta-heuristic based approaches, J. Intell. Manuf. 28 (2017) 95–109, doi:10.1007/s10845-014-0964-x.
[58] K. Taxakis, C. Papadopoulos, A design model and a production–distribution and inventory planning model in multi-product supply chain networks, Int. J. Prod. Res. 54 (2016) 6436–6457, doi:10.1080/00207543.2016.1158882.
[59] H.-Y. Kang, W.L. Pearn, I.-P. Chung, A.H.I. Lee, An enhanced model for the integrated production and transportation problem in a multiple vehicles environment, Soft Comput. 20 (2016) 1415–1435, doi:10.1007/s00500-015-1595-7.
[60] J. Shao, D. Ke, Lot sizing, pricing and lead time decisions with time and price sensitive demand, in: Proceedings of IEEE Asia-Pacific Conference on Services Computing, APSCC '06, 2006, pp. 130–137, doi:10.1109/APSCC.2006.69.
[61] A. Senoussi, N.K. Mouss, B. Penz, N. Brahimi, S. Dauzère-Pérès, Modeling and solving a one-supplier multi-vehicle production-inventory-distribution problem with clustered retailers, Int. J. Adv. Manuf. Technol. 85 (2016) 971–989, doi:10.1007/s00170-015-7966-5.
[62] Z. Chen, B.R. Sarker, An integrated optimal inventory lot-sizing and vehicle-routing model for a multisupplier single-assembler system with JIT delivery, Int. J. Prod. Res. 52 (2014) 5086–5114, doi:10.1080/00207543.2014.899715.
[63] G. Liotta, G. Stecca, T. Kaihara, Optimisation of freight flows and sourcing in sustainable production and transportation networks, Int. J. Prod. Econ. 164 (2015) 351–365, doi:10.1016/j.ijpe.2014.12.016.
[64] J. Mula, R. Poler, J.P. Garcia, MRP with flexible constraints: a fuzzy mathematical programming approach, Fuzzy Sets Syst. 157 (2006) 74–97, doi:10.1016/j.fss.2005.05.045.
[65] K.H. Chuah, J.C. Yingling, Routing for a just-in-time supply pickup and delivery system, Transp. Sci. 39 (2005) 328–339, doi:10.1287/trsc.1040.0092.
[66] H.P. Williams, Model Building in Mathematical Programming, 4, John Wiley & Sons, 2013.
[67] C.E. Miller, A.W. Tucker, R.A. Zemlin, Integer programming formulation of traveling salesman problems, J. ACM 7 (1960) 326–329, doi:10.1145/321043.321046.

[68] G. Desaulniers, Managing large fixed costs in vehicle routing and crew scheduling problems solved by column generation, Comput. Oper. Res. 34 (2007) 1221–1239, doi:10.1016/j.cor.2005.07.002.
[69] D. Peidro, M. DÍaz-Madroñero, J. Mula, An interactive fuzzy multi-objective approach for operational transport planning in an automobile supply chain, WSEAS Trans. Inf. Sci. Appl. 7 (2010) 283–294.
[70] Díaz-Madroñero M., Peidro D., Mula J. Supply Chain Operational Transport Planning by Using an Interactive Fuzzy Multi-Objective Linear Programming Approach. Dir Y Organ 2012;46:31–44.
[71] K.R. Baker, An experimental study of the effectiveness of rolling schedules in production planning, Decis. Sci. 8 (1977) 19–27, doi:10.1111/j.1540-5915.1977.tb01065.x.
[72] M. Mohammadi, S.M.T. Fatemi Ghomi, B. Karimi, S.A. Torabi, Rolling-horizon and fix-and-relax heuristics for the multi-product multi-level capacitated lotsizing problem with sequence-dependent setups, J. Intell. Manuf. 21 (2010) 501–510, doi:10.1007/s10845-008-0207-0.
[73] R. Ramezanian, M. Saidi-Mehrabad, P. Fattahi, MIP formulation and heuristics for multi-stage capacitated lot-sizing and scheduling problem with availability constraints, J. Manuf. Syst. 32 (2013) 392–401, doi:10.1016/j.jmsy.2013.01.002.
[74] A. Agra, M. Christiansen, A. Delgado, L. Simonetti, Hybrid heuristics for a short sea inventory routing problem, Eur. J. Oper. Res. 236 (2014) 924–935, doi:10.1016/j.ejor.2013.06.042.
[75] J.G. Rakke, M. Stålhane, C.R. Moe, M. Christiansen, H. Andersson, K. Fagerholt, et al., A rolling horizon heuristic for creating a liquefied natural gas annual delivery program, Transp. Res. Part C Emerg. Technol. 19 (2011) 896–911, doi:10.1016/j.trc.2010.09.006.
[76] Maximal Software Incorporation. MPL Modeling System Release 4.2n 2014.
[77] Gurobi Optimization Incorporation. Gurobi 5.6.2 2014.
[78] M. Boudia, C. Prins, A memetic algorithm with dynamic population management for an integrated production-distribution problem, Eur. J. Oper. Res. 195 (2009) 703–715.
[79] G.F. Knolmayer, P. Mertens, A. Zeier, Supply Chain Management Based on Sap Systems: Order Management in Manufacturing Companies, Springer Science & Business Media, 2002.
[80] H. Stadtler, Supply Chain Management and Advanced Planning: Concepts, Models, Software, and Case Studies, in: H. Stadtler, C. Kilger, H. Meyr (Eds.), Springer, Berlin, Heidelberg, 2015 editors, doi:10.1007/978-3-642-55309-7_1.
[81] Y. Mauergauz, Advanced Planning and Scheduling in Manufacturing and Supply Chains, Springer, 2016.
[82] C. Archetti, M.G. Speranza, Vehicle routing problems with split deliveries, Int. Trans. Oper. Res. 19 (2012) 3–22, doi:10.1111/j.1475-3995.2011.00811.x.
[83] H. Kagermann, W. Wahlster, J. Helbig, Securing the Future of German Manufacturing Industry: Recommendations for Implementing The Strategic Initiative INDUSTRIE 4.0, Acatech – National Academy of Science and Engineering, 2013, pp. 1–84. Final Report of the Industrie 4.0 Working Group, doi:10.13140/RG.2.1.1205.8966.
[84] Dujin A., Geissler C., Horstkötter D. Think Act Industry 4.0. The New Industrial Revolution: How Europe will Succeed 2014.
[85] R. Aboutalebi, The taxonomy of international manufacturing strategies, in: L. Brennan, A. Vecchi (Eds.), International Manufacturing Strategy in a Time of Great Flux editors, Springer International Publishing, Cham, 2017, pp. 17–41, doi:10.1007/978-3-319-25351-0_2.